Analysis of a Passive Aeration Concept to Treat Swine Waste with Dead-End, Oxygen-Permeable Membrane Tubes

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ABSTRACT

Jing Deng: Analysis of a Passive Aeration Concept to Treat Swine Waste
with Dead-End, Oxygen-Permeable Membrane Tubes
(Under the direction of Michael D. Aitken)

The conventional method of managing swine waste using open lagoons with spray irrigation is still nearly universal in North Carolina. This project seeks to explore a new technology for anaerobic swine lagoons, that is, to apply dead-end, oxygen-permeable membrane tubes individually in lagoons, which could passively provide oxygen to further treat the anaerobically digested waste. The major advantage of such a system would be near-ideal oxygen transfer efficiency and no energy cost to supply oxygen. A membrane tube model was developed to quantify oxygen concentration gradient along the tube length and rate of oxygen mass transfer through the membrane wall. From the model, I find that oxygen concentration hardly changes along the tube, and oxygen mass transfer rate is directly related to tube parameters, especially the membrane thickness. To quantify a potential full-scale application, the lagoons at Butler Farm in Lillington, NC are used as a case study. Using waste characteristics of the anaerobically digested swine waste at Butler Farm, about 12,100 membrane tubes would be needed to meet the oxygen demand in this lagoon. Finally, membrane tube manufacture, tube supporting systems and tube maintenance issues must be considered before it can be implemented in reality.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

C	Oxygen concentration at distance x in the tube, mg/cm^3
C_0	Oxygen concentration at x = 0 (tube entrance), 0.271 mg/cm^3
C_L	Oxygen concentration at x = L (tube entrance), mg/cm^3
D	Oxygen diffusion coefficient in air, cm^2/s
D_m	Oxygen diffusion coefficient in membrane, cm^2/s
K_g	Membrane/gas partition coefficient
L	Length of tube, cm
M	Oxygen mass transfer rate, mg/s
M_{O2}	Oxygen molecular weight, 32 g/mol
N_r	Radial flux of oxygen, mg/cm^2-s
N_R	Radial flux of oxygen at r = R, mg/cm^2-s
N_x	Vertical flux of oxygen. mg/cm^2-s
P	Oxygen partial pressure in tube, pa
r	Radial distance, cm
R	Tube radius, cm
R^*	Universal gas constant, 8.314 $m^3 \cdot Pa/(K \cdot mol)$
T	Temperature, 298 K
μ	Dynamic viscosity of air, 1.86×10^{-5} kg/m-s

v	Gas velocity in tube, cm/s
v_0	Gas velocity at x = 0, cm/s
$\bar{v}$	Average gas velocity in the cross-section of tube, cm/s
$v(r)$	Gas velocity in the radial distance r, cm/s
$v(0)$	Gas velocity in the radial distance r = 0, cm/s
v_{mas}	Maximum gas velocity in the cross-section of tube, $v_{mas} = v(0)$, cm/s
x	Distance along the tube, cm
δ	Tube wall thickness, cm

1.0 INTRODUCTION

Swine farming and pork production processing are major industries in North Carolina, especially for the eastern part of the state. As of the most recent Agriculture Census, in 2002, North Carolina ranks as the second-largest hog farming state in the country, after Iowa. Pigs have been a historical part of the state's agriculture, but it was in the 1990s that the hog farming had experienced exponential growth. Within a decade, the hog population jumped from around 2.6 million in 1988 to over 8 million in 1997[1]. Although the total population of hogs increased, the total number of hog farms declined. In 1986, there were 15,000 farms with at least one head of hogs in the state. By the year 2006, there were only 2,300 such farms remaining[1].

Before, people who raised hogs kept small numbers of animals that roamed in outdoor fields, where their droppings fertilized crops. However, with the industry consolidation, most of the farms that survived did so by going big - raising thousands of animals that spend their entire lives inside barns. These hogs collectively produce 40 million gallons of untreated manure and other waste each day[2]. To handle all that waste, farmers in North Carolina usually use a standard waste treatment technology – earthen anaerobic lagoons coupled with field application[3]. Hog feces and urine fall through the slatted floors of barns into a pit under the building. Then the waste is flushed into open lagoons where it is degraded by anaerobic microorganisms. After that, farmers will spray the lagoon liquid onto agriculture fields nearby.

It seems that anaerobic lagoon and spray field system created an economically feasible development for farmers, allowing them to raise hogs and grow crops on the same farm. But actually this system could create serious public health and environmental consequences. Lagoon liquid contains significant amounts of nitrogen and phosphorus. If lagoons overflow or leak, the liquid will enter waterways. Then these nutrients fuel algae and other aquatic plant growth. With enough nitrogen and phosphorus, algal blooms can deplete the oxygen in the water, resulting in fish kills and serious odor problems. Noxious odors, caused by hydrogen sulfide, ammonia and other gases, are also emitted from lagoons and sprayed liquid. Studies have shown that neighbors of these facilities suffer from respiratory problems, anxiety and sleep disturbances that can be attributed to exposure to farm emissions[4].

Over the past two decades, much work has been done to regulate the environmental and human health impacts of hog lagoons in North Carolina. Since 1997, new hog lagoons cannot be constructed if they do not use innovative technologies. The 2007 Swine Farm Environmental Performance Standards Act[5], enacted by the North Carolina legislature, banned the construction of new swine farms that use open anaerobic lagoons coupled with land application as the primary methods of waste treatment and disposal. New farms must employ technologies that meet environmental performance standards[5]. The standards seek to substantially eliminate emissions of various pollutants to surface water, groundwater, soil and air, including the emission of animal waste, odor, pathogens, nutrients, heavy metals and ammonia. However, there are no treatment performance requirements for existing farms. So the conventional method of managing swine waste using open lagoons with spray irrigation is still universal in North Carolina.

This project seeks to explore a new technology for anaerobic swine lagoons, which can help minimize its environmental and human health impacts while remaining technically and economically feasible. The technology consists of applying dead-end, oxygen-permeable membrane tubes individually in lagoons, providing oxygen passively to further treat the anaerobically digested waste. In particular, the technology is intended to oxidize ammonia in the waste, thus minimizing the potential for the emission of ammonia from the waste to the atmosphere. The oxygen mass transfer rate through the membrane wall is calculated under ideal conditions. If it is enough to meet the oxygen demand in lagoons at reasonable cost, then this technology might be possible to be applied in practice.

2.0 BACKGROUND

2.1 Relevant Biological Processes

The technology in this report seeks to further treat the anaerobically digested waste in lagoons through nitrification. During the anaerobic digestion, organic matter in lagoon liquid is degraded to methane, carbon dioxide, water, and soluble or particulate organic products.

Nitrification is a two-step process: oxidation of ammonium to nitrite and oxidation of nitrite to nitrate.

$$\mathrm{NH_4}^{+} + 1.50_2 \rightarrow \mathrm{NO_2}^{-} + \mathrm{H_2O} + 2\mathrm{H}^{+}$$

$$\mathrm{NO_2}^{-} + 0.50_2 \rightarrow \mathrm{NO_3}^{-}$$

The overall equation is

$$\mathrm{NH_4}^{+} + 20_2 \rightarrow \mathrm{NO_3}^{-} + \mathrm{H_2O} + 2\mathrm{H}^{+} \tag{1}$$

Converting molar units to mass units, 1 kg of NH_4^+-N requires 4.57 kg O_2 for complete nitrification.

During denitrification, nitrate and organic matter (COD) are consumed to produce carbon dioxide, nitrogen, water and alkalinity. Qualitatively, the equation can be written as:

$$\mathrm{COD} + \mathrm{NO_3}^{-} \rightarrow \mathrm{C0_2} + 0.5\mathrm{N_2} + \mathrm{H_2O} + \mathrm{OH}^{-} \tag{2}$$

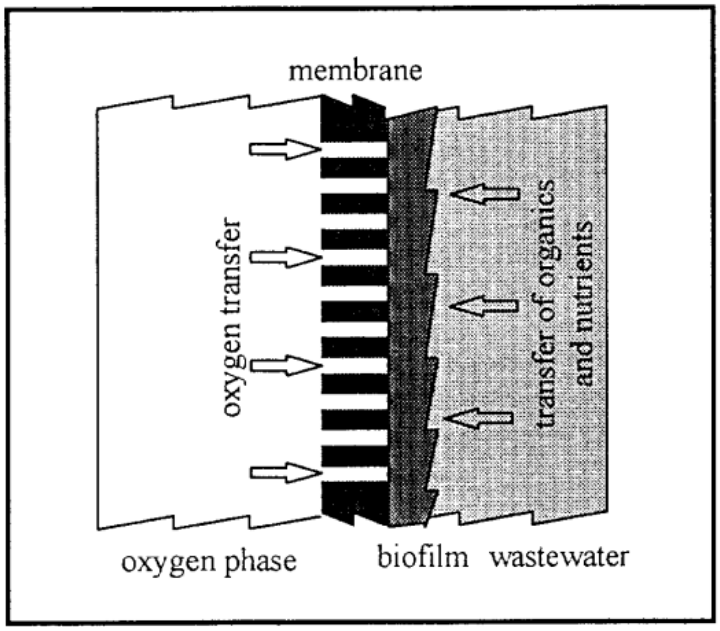
2.2 Typical Composition of Anaerobically Digested Waste in Lagoons

In a conventional swine farm, new water entering the lagoons is a combination of urine, feces, waste drinking water and any fresh water used to wash the barns. Note that the standard practice in North Carolina is to flush waste from the barns using lagoon liquid. During anaerobic digestion, most of the biodegradable COD is consumed. Methane, along with carbon dioxide, water and trace gases, are produced. A small concentration of biodegradable COD and relatively high concentration of ammonium are left in the digested waste.

2.3 Membrane Aeration Bioreactor

The idea of using dead-end membrane tubes comes from previous work on membrane aeration of bioreactors. The membrane aeration bioreactor is a small footprint modular process, suited to on-site treatment of high-organic-strength industrial wastewater. Membrane aeration bioreactor research has focused on hollow fibers, with the oxygen phase on the lumen side and the biofilm attached to the shell side over which wastewater flows (Figure 1)[6]. Hollow fibers provide a large surface area for oxygen transfer and biofilm growth while occupying a relatively small volume in the bioreactor. In the past, inadequate oxygen transfer rates with hollow fiber membranes has made the culture of microbial cells with high oxygen demand difficult. Later a bubbleless hollow fiber membrane aerator capable of high oxygen transfer efficiency has been developed. The fibers in these modules are sealed at one end so that oxygen inside the lumen transfers across the gas-permeable membrane by diffusion without bubble formation[7]. The fibers have a low mass transfer resistance and can be operated at high gas pressures, thus allowing them to meet high aeration requirements. Brindle et al. (1998) demonstrated that a 100% oxygen-use efficiency can be achieved when using dead-end hollow fibers for the oxidation of a synthetic wastewater[8].

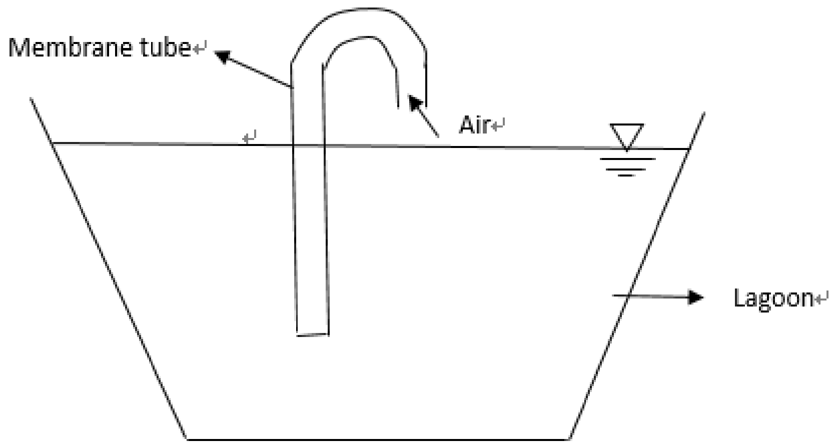
Figure 1: Schematic of the MABR process with a biofilm attached to the wastewater side of the membrane (reproduced from Brindle[6])



2.4 Dead-End Membrane Tubes

To take advantage of very high oxygen transfer efficiency, we are thinking of using a similar technology in hog waste lagoons. Instead of using bundles of hollow fibers in bioreactors, dead-end membrane tubes open to the atmosphere would be applied individually (Figure 2). The membrane we are considering is hydrophobic and nonporous, so that oxygen will dissolve in the membrane itself and be transferred by gaseous diffusion. Additionally, ambient air can be used as the source of oxygen instead of compressed pure oxygen, because in a typical aerobic wastewater treatment system, aeration represents the major cost of operation. If only ambient air is used, it will reduce energy consumption and the overall cost of treatment. When oxygen is consumed on the liquid-side surface of the membrane, the relatively high oxygen concentration gradient encourages the oxygen to diffuse across the porous membrane wall, and to dissolve directly into the water without the formation of bubbles.

Figure 2: Sketch of dead-end membrane tube applied in lagoon



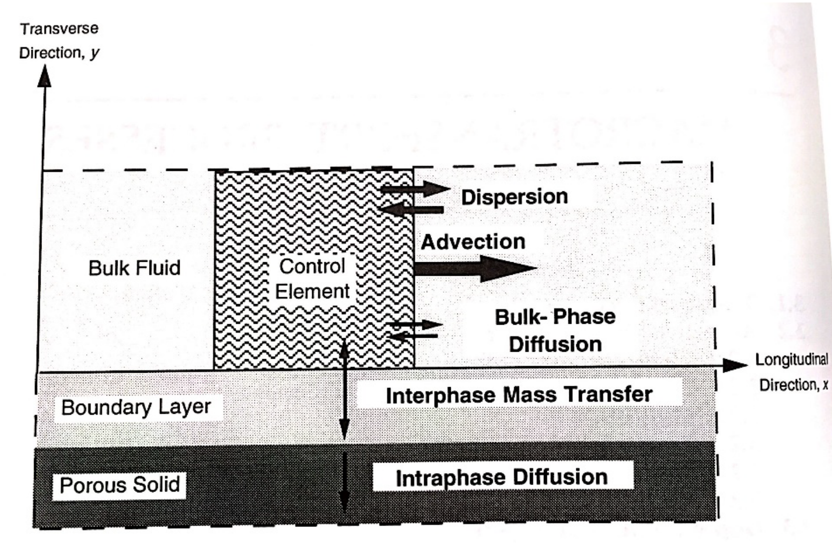
Based on this general idea, I have built a mathematical model to quantify oxygen concentration gradient along the tube length and rate of oxygen mass transfer through the membrane wall of a single tube. If it can be concluded that the oxygen mass transfer rate is high enough to meet the oxygen demand of digested waste, then it might be possible to use this technology in practice. If using only ambient air is practicable, that means a lot of energy used to pump oxygen is saved. And it therefore saves money and does not need complex treatment facilities.

3.0 OXYGEN TRANSFER MODEL FORMULATION

3.1 Mechanisms of oxygen transfer in the tube

In order to quantify the oxygen concentration gradient in the tube and rate of oxygen transfer through the membrane wall, firstly, mechanisms of mass transfer in the membrane tube need to be analyzed. Figure 3 illustrates the possible transport processes in environmental systems.

Figure 3: Mechanisms of mass transport and transfer (reproduced from Weber and DiGiano[9])



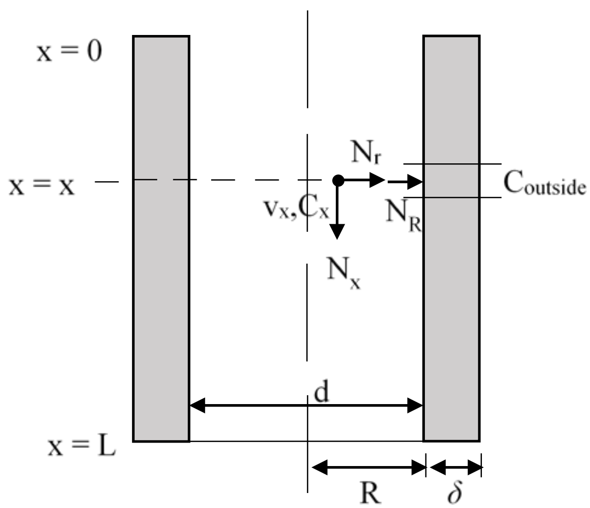
The envisioned system is for an air-filled tube suspended in a relatively quiescent liquid, with no bulk fluid flow. However, there are bulk-phase diffusion and intraphase diffusion in our model. And I assume that there is no turbulence in the tube, so dispersion can be ignored. As for advection inside the tube, according to its definition, substance mass is carried along with fluid mass. This type of transport is characterized directly by bulk flow conditions of a system. In our case, it seems that diffusion is the main mechanism for oxygen transfer in air, because the rate of oxygen diffusing out through the membrane wall is very slow. Although it seems that there should be no bulk flow of air inside the tube, in my model advection is still taken into consideration.

3.2 Model formulation

3.2.1 Model sketch

The definition sketch for the model of an air-filled tube in contact with an oxygen-consuming phase on the tube exterior is shown in Figure 4.

Figure 4: Definition sketch of model



Where:

C_x = C = Oxygen concentration at distance x in the tube, mg/cm^3

L = Length of tube, cm

N_r = Radial flux of oxygen, mg/cm^2-s

N_R = Radial flux of oxygen at r = R, mg/cm^2-s

N_x = Vertical flux of oxygen. mg/cm^2-s

r = Radial distance, cm

R = Tube radius, cm

$v_x = v$ = Gas velocity in tube, cm/s

x = Distance along the tube, cm

δ = Tube wall thickness, cm

3.2.2 Mass balance

As the tube is cylindrical, it is appropriate to write the mass balance equation in cylindrical coordinates, instead of rectangular coordinates. In cylindrical coordinates,

$$-\nabla \cdot \vec{N} = -\frac{1}{r}\frac{\partial}{\partial r}(r \cdot N_r) - \frac{\partial N_x}{\partial x} = \frac{\partial C}{\partial t} \tag{3}$$

For N_r, we only care about N_R, i.e., the radial flux at the inside surface of the membrane wall, which influences the diffusion through the membrane wall. So I average N_r in the cross-section of the tube.

$$\frac{1}{\pi R^2}\int_0^R \left[-\frac{1}{r}\frac{\partial}{\partial r}(r \cdot N_r) - \frac{\partial N_x}{\partial x} - \frac{\partial C}{\partial t}\right] \cdot 2\pi r\, dr = 0$$

The result is

$$-\frac{\partial N_x}{\partial x} - \frac{2}{R}N_R = \frac{\partial C}{\partial t} \tag{4}$$

Assuming steady state

$$-\frac{dN_x}{dx} - \frac{2}{R}N_R = 0 \tag{5}$$

The flux of oxygen in the vertical direction, N_x, is defined as the mass of oxygen diffusion and the mass carried along by bulk flow in the tube.

$$N_x = -\mathrm{D}\frac{dC}{dx} + Cv \tag{6}$$

Where:

D = Oxygen diffusion coefficient in air, cm^2/s

The flux of oxygen in the radial direction, N_R, is defined as the mass of oxygen diffusion through the membrane wall. If an aerobic biofilm is attached to the exterior surface of the membrane, we can assume that the oxygen concentration at the outside of the membrane wall is zero. In addition, the effect of the pressure differential between the two sides of the membrane on oxygen transport is not considered. Therefore,

$$N_R = D_m \cdot \frac{K_g C - 0}{\delta} \tag{7}$$

Where:

D_m = Oxygen diffusion coefficient in membrane, cm^2/s

K_g = Membrane/gas partition coefficient

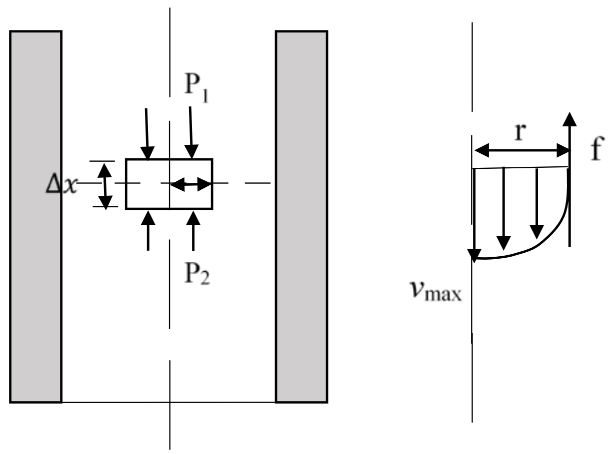
After combining equations (5), (6) and (7), and simplifying, we can get

$$\mathrm{D}\frac{d^2C}{dx^2} - C\frac{dv}{dx} - v\frac{dC}{dx} - \frac{2D_m K_g}{R\delta}C = 0 \tag{8}$$

3.2.3 Momentum analysis

Advective flow has been assumed to exist in the model. A pressure difference along the length of the tube is caused by oxygen concentration changes in air due to oxygen diffusing out through the membrane wall. Advection could be caused by such a pressure difference, which provides force for air to flow. Thus, we can conduct a force analysis for an element of air in the tube.

Figure 5: Illustration of force analysis on an element of air



Considering a small cylinder element, there are two forces on it. One is caused by pressure (P_1 and P_2). The other is caused by shear resistance (f) due to fluid viscosity. Because the whole tube is assumed to be at steady state, we can study an infinitesimal free body diagram to obtain the force equilibrium. The resulting equation can be written as follows.

$$(P_1 - P_2)\pi r^2 = -\mu \frac{dv}{dr} \cdot (2\pi r \Delta x) \tag{9}$$

Where:

P = Oxygen partial pressure in tube, pa

μ = Dynamic viscosity of air, kg/m-s

v(r) = Gas velocity in the radial distance r, cm/s

v(0) = Gas velocity in the radial distance r = 0, cm/s

v_{mas} = Maximum gas velocity in the cross-section of tube, $v_{mas} = v(0)$, cm/s

Rearranged,

$$-\frac{dv}{dr} = \frac{P_1 - P_2}{2\mu \Delta x} \cdot r \tag{10}$$

Integrating both sides of equation (10),

$$\int_0^r -\frac{dv}{dr}dr = \int_0^r \frac{P_1 - P_2}{2\mu\Delta x} \cdot r\, dr$$

$$-v(r) + v(0) = \frac{P_1 - P_2}{4\mu\Delta x} r^2 \tag{11}$$

And when r = R, v(R) = 0. Thus, the corresponding velocity at the center of the tube (r = 0) is

$$v(0) = v_{max} = \frac{P_1 - P_2}{4\mu\Delta x} R^2 \tag{12}$$

Substituting equation (12) into equation (11), we can get

$$v(r) = v(0) - \frac{P_1 - P_2}{4\mu\Delta x} r^2 = \frac{P_1 - P_2}{4\mu\Delta x}(R^2 - r^2) \tag{13}$$

Therefore v(r), the velocity of air in this element, is a function of radius. In order to simplify the model, just like with N_r, I average v(r) in the cross-section of the tube.

$$\bar{v} = \frac{1}{\pi R^2}\int_0^R v(r) \cdot 2\pi r \cdot dr$$

$$= \frac{1}{\pi R^2}\int_0^R \frac{P_1 - P_2}{4\mu\Delta x}(R^2 - r^2) \cdot 2\pi r \cdot dr$$

$$= \frac{P_1 - P_2}{8\mu\Delta x} \cdot R^2 \tag{14}$$

This equation truly reflects that velocity is caused by a pressure difference. Furthermore, pressure is a function of concentration. In this model, I assume that only oxygen permeates the membrane. So the pressure difference is caused by the oxygen concentration change in air. If oxygen concentration changes along the tube length, we can write the following equations.

$$PV = nR^*T$$

$$PV = \frac{m}{M_{O_2}} R^*T$$

$$\mathrm{P} = \frac{C(R^*T)}{M_{O_2}}$$

$$P_1 - P_2 = (C_1 - C_2)\frac{R^*T}{M_{O_2}} = -\Delta\mathrm{C}\cdot\frac{R^*T}{M_{O_2}} \tag{15}$$

Where:

M_{O_2}= Oxygen molecular weight, 32 g/mol

R* = Universal gas constant, 8.314 $m^3 \cdot Pa/(K \cdot mol)$

T = Temperature, 298 K

$\bar{v}$ = Average gas velocity in the cross-section of tube, cm/s

Then, substituting equation (15) into equation (14), I get

$$\bar{v} = \frac{P_1 - P_2}{8\mu\Delta x}\cdot R^2 = -\frac{R^2(R^*T)}{8\mu M_{O_2}}\cdot\frac{\Delta\mathrm{C}}{\Delta x} \tag{16}$$

Regarding a very thin slice, equation (16) can be written as

$$\bar{v} = -\frac{R^2(R^*T)}{8\mu M_{O_2}}\cdot\frac{dC}{dx} \tag{17}$$

3.2.4 Model formulation

Combining equation (17) with equation (8), I get

$$\mathrm{D}\frac{d^2C}{dx^2} + C\cdot\frac{R^2(R^*T)}{8\mu M_{O_2}}\cdot\frac{d^2C}{dx^2} + \frac{R^2(R^*T)}{8\mu M_{O_2}}\cdot\left(\frac{dC}{dx}\right)^2 - \frac{2D_mK_g}{R\delta}C = 0 \tag{18}$$

The boundary conditions for the above equation are: at x = 0 cm, C = C_0 = 0.271 mg/cm^3 (concentration of oxygen in standard air at one atmosphere, 298K); at x = L, v = 0 cm/s (dead-end). Equation (18), subject to these boundary conditions, is solved using Mathematica to give the oxygen concentration and bulk flow velocity along the tube. Then the rate of oxygen diffusing out through the membrane wall can be calculated as shown below.

$$M = \int_0^L N_R \cdot 2\pi R \cdot dx = \int_0^L \frac{D_m K_g C}{\delta} \cdot 2\pi R \cdot dx = \frac{2\pi R D_m K_g}{\delta} \int_0^L C\, dx \quad (19)$$

3.3 Case analysis

In order to verify whether the model derived above makes sense, a particular membrane material and tube parameters are chosen to calculate the oxygen concentration along the tube and transfer rate of one tube. The membrane material is silastic tubing (PDMS, DOW Corning). The parameters of the tube are listed in Table 1. I used Mathematica to solve the nonlinear second order differential equation (19) numerically, and plot the results below (Figures 6 and 7).

Table 1: Membrane tube parameters

Parameter	Value
R	1.00 cm
D_m [10]	0.0000222 cm^2/s
K_g [10]	0.22
L	200 cm
δ	0.06 cm

Figure 6: Oxygen concentration vs. tube length

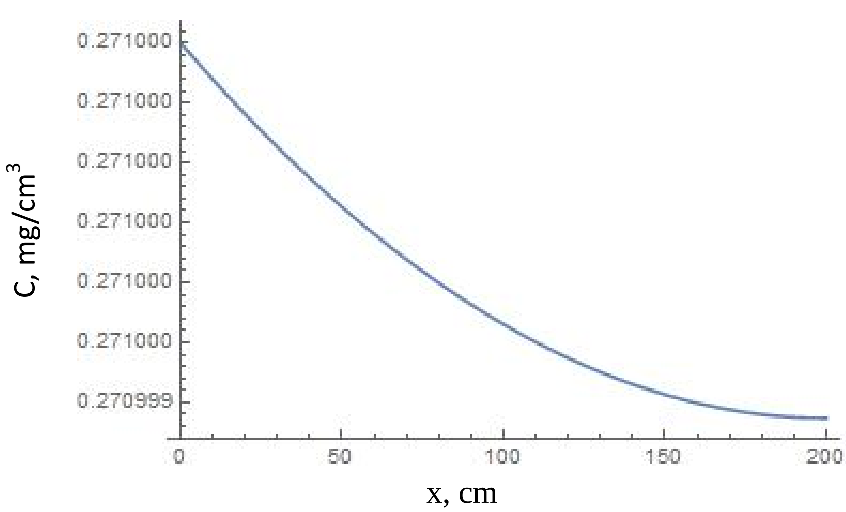
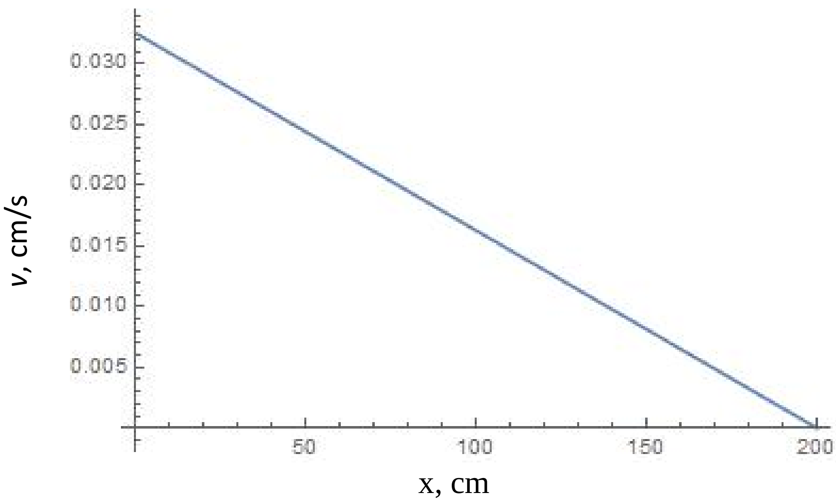


Figure 7: Velocity vs. tube length



At x = 200 cm (bottom of the tube), C = C_L = 0.270999 mg/cm^3; at x = 0 cm, v = 0.033 cm/s. Then the rate of oxygen diffusing out through membrane tube is

$$M = \int_0^L N_R \cdot 2\pi R \cdot dx = \int_0^L \frac{D_m K_g C}{\delta} \cdot 2\pi R \cdot dx = \frac{2\pi R D_m K_g}{\delta} \int_0^L C\, dx$$

Use Mathematica to calculate

$$\int_0^L C\, dx = 54.2 \approx C_0 \times L$$

Where:

C_0 = Oxygen concentration at x = 0 (tube entrance), 0.271 mg/cm^3

L = length of membrane tube, cm

v_0 = Gas velocity at x = 0, cm/s

Thus, M = 0.0277 mg/s = 2394 mg/d.

From the results, we can find that the concentration of oxygen hardly changes along the tube, though there is oxygen diffusing out through the membrane wall. So, in this case it is appropriate to simplify the model in a way that the tube can be treated as a homogeneous unit; that is, there is no concentration variation along the tube length. The term $\int_0^L C\,dx$ can then be replaced by $C_0 \times L$. In order to see whether this simplification is reasonable or not, more sets of tube parameters were selected to do the same calculation. Results are shown in Table 2.

Table 2: Results for various cases of parameter values

Case No.	R, cm	δ, cm	L, cm	C_L, mg/cm^3	v_0, cm/s	$\int_0^L C\,dx$	$C_0 \times L$	M, mg/s	M, mg/d
1	1.00	0.06	200	0.270999	0.033	54.2	54.2	0.0277	2393.851
2	2.00	0.015	400	0.270999	0.130	108.4	108.4	0.4433	38301.61
3	0.25	0.1	200	0.270976	0.078	54.197	54.2	0.0042	359.0564
4	0.25	0.015	200	0.27084	0.521	54.179	54.2	0.0277	2392.906
5	2.00	0.1	200	0.271	0.0097	54.2	54.2	0.0332	2872.621
6	2.00	0.015	200	0.271	0.0652	54.2	54.2	0.2217	19150.81

All the values for radius and thickness I chose are in the expected ranges for practical application, i.e., R: 0.25 cm – 2.0 cm, δ: 0.015 cm – 0.1 cm. It is not difficult to find that in all the cases, oxygen concentration at the bottom of the tube, C_L, is very close to oxygen concentration at the top, i.e., 0.271 mg/cm^3. And $\int_0^L C\,dx$ is equal to $C_0 \times L$ to at least three significant figures. Cases where radius and thickness are beyond our consideration are also chosen to do the same calculation. The results are shown in Table 3, from which we can find that when radius and thickness are very large (case No.7), the result still meets our assumption. Furthermore, when radius and thickness are very small (case No.8), C_L is still quite close to 0.271 mg/cm^3, and there is not a very big difference between $\int_0^L C\,dx$ and $C_0 \times L$.

Table 3: Results for additional cases of parameter values

Case No.	R, cm	δ, cm	L, cm	C_L, mg/cm^3	v_0, cm/s	$\int_0^L C\,dx$	$C_0 \times L$	M, mg/s	M, mg/d
7	10	1	200	0.271	0.000195	54.2	54.2	0.0166	1436.31
8	0.1	0.01	200	0.267	1.9356	53.7	54.2	0.0165	1423.06

From what I have discussed above, it is appropriate to assume that there is no oxygen concentration variation inside the tube. Thus, the rate of oxygen diffusing out through the membrane can be calculated as

$$M = \frac{2\pi R D_m K_g}{\delta}\int_0^L C\,dx \approx \frac{2\pi R D_m K_g}{\delta} C_0 L \tag{20}$$

In addition, gas velocity inside the tube is very small. Reynolds numbers calculated are all smaller than 2100, which verifies the bulk flow in the tube is laminar flow. Thus, it is consistent with the assumption that dispersion in the tube can be ignored.

3.4 Parameters analysis

From the model we can see that tube radius, thickness, length and membrane material will decide the rate of oxygen transfer. If we want to obtain a higher mass transfer rate, we firstly need to know how the rate is going to change if parameters change. And if cost is related to the amount of membrane material required, a membrane tube that can provide more oxygen, and at the same time cost less, would be our best choice.

3.4.1 Tube radius and thickness

From equation (20), we can find that mass transfer rate will go up as tube radius becomes larger and tube thickness becomes smaller. But as tube radius becomes larger, more material is needed. So we have to make a trade-off between mass transfer rate and cost. In order to quantify the trade-off, ratios between mass transfer rate and mass of membrane material are compared for different tube radius and thickness. Because only radius and thickness are studied, the membrane material and tube length are fixed. I chose PDMS as the membrane material, and tube length is assumed to be 200 cm (corresponding to an assumed liquid depth in a swine waste lagoon of at least 2 m). Acceptable radius and thickness ranges are R: 0.25 cm – 2.0 cm, δ: 0.015 cm – 0.1 cm. Boundary and median values are chosen. The calculation results are shown in Table 4.

Table 4: Comparison of ratios between mass transfer rate and mass of membrane material

Case No.	R, cm	δ, cm	L, cm	M, mg/s	M, mg/d	Mass of material, mg	Ratio, d^{-1}
1	1	0.06	200	0.0277	2393.85	74904.07	0.03196
2	0.25	0.1	200	0.0042	359.056	36361.2	0.00988
3	0.25	0.015	200	0.0277	2392.91	4681.505	0.51114
4	2	0.1	200	0.0332	2872.62	248468.2	0.01156
5	2	0.015	200	0.2217	19150.8	36497.55	0.52472

We can find that when R is the same, different thicknesses could cause a very different ratio. For example, comparing Cases 2 and 3, both have a radius of 0.25 cm, a 7-fold decrease in thickness results in an about 50-fold increase in the ratio. The same result can be found in Cases 4 and 5. However, if thickness is the same, different values of R result in a similar ratio. Comparing Cases 2 and 4, both have a thickness 0.1 cm, but an 8-fold increase in radius results in a small change in the ratio. Thus, if we want a higher mass transfer rate as well as a relatively low cost, a smaller thickness is the key parameter.

3.4.2 Tube length

From the model we can find that oxygen transfer rate is proportional to tube length, which is which is also true for the mass of material. So in theory, only changing tube length will not change ratios between mass transfer rate and mass of membrane material.

3.4.3 Membrane material

Two parameters in equation (20) are determined by the membrane material, i.e., D_m and K_g. And mass transfer rate is also proportional to these two parameters. Therefore, it is important to find a kind of membrane material which can provide a relatively high oxygen diffusivity.

Robb[11] has tabulated O_2 permeabilities in various membranes. Table 5 table shows that not only standard dimethyl silicone rubber but also many silicone derivatives have O_2 permeabilities higher than even the most permeable nonsilicone plastics.

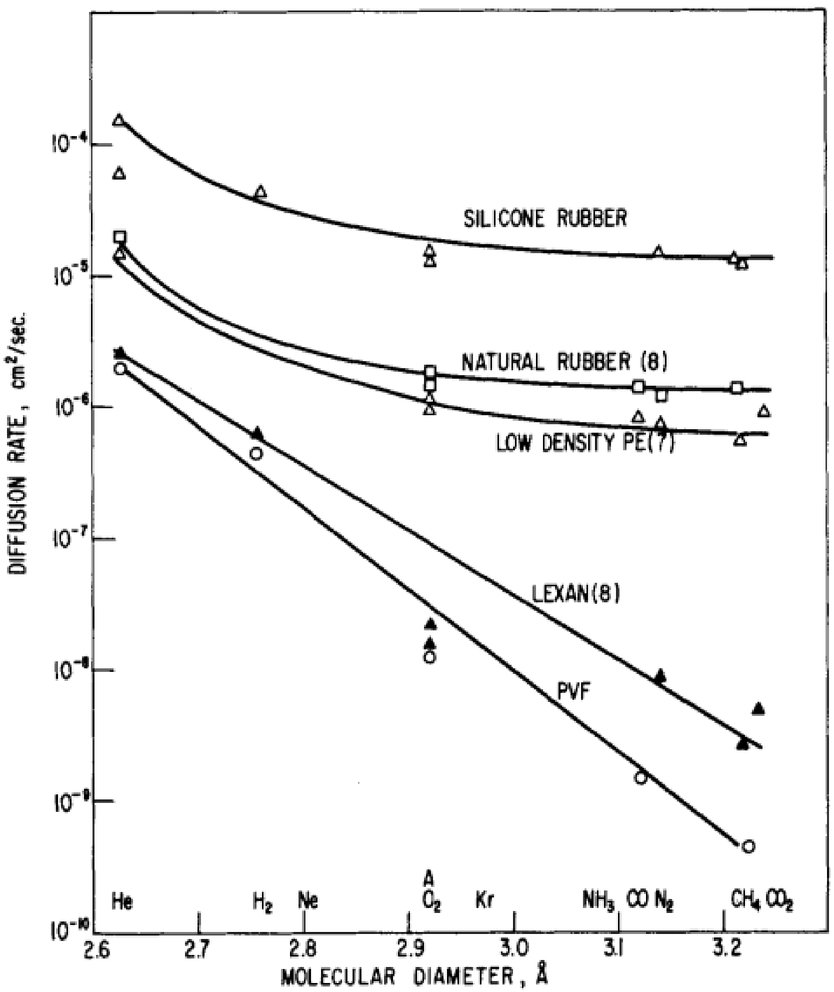
Table 5: O_2 permeabilities in various polymers (reproduced from Robb[11])

Polymer	$\mathrm{Pt}_{O_2}{}^{a} \times 10^9$
Dimethyl silicone rubber	60
Fluorosilicone	11
Nitrile silicone	8.5
Natural rubber	2.4
Ethyl cellulose	2.1
Polyethylene, low density	0.8
BPA polycarbonate	.16
Butyl rubber	.14
Polystyrene	.12
Polyethylene, high density	.1
Cellulose acetate	.08
Methyl cellulose	.07
Polyvinyl chloride	.014
Polyvinyl alcohol	.01
Nylon 6	.004
Polyvinylidene fluoride	.003
Mylar	.0019
Kel F (unplasticized)	.001
Vinylidene chloride – vinyl chloride	.0005
Teflon	.0004

[a] Permeability of oxygen in membrane, $\frac{\text{cc's (RTP), cm}}{\text{sec, sq cm, cm Hg } \Delta P}$

It is proposed that the permeability constant (P) for oxygen is the product of the diffusion rate (D) and solubility (S); i.e., P=D*S. And the solubility of O_2 measured in silicone rubber is comparable to that reported for other polymers. On the other hand, it seems that the diffusion rate of O_2 in silicone rubber is almost an order of magnitude higher than diffusion rates for O_2 in the most permeable hydrocarbon polymers[11]. This is shown in Figure 8, from which we can find that the unusually high permeability in silicone rubber is mainly due to the high rate of diffusion of O_2.

Figure 8: Diffusion rates of dissolved gases in polymers (reproduced from Robb[11])



The oxygen diffusion coefficient, D_m, used in the calculations above (2.2×10^{-5} cm^2/s), is from PDMS. Polydimethyl silicone membranes (PDMS) are more than 30 times more permeable than non-silicone stable polymers[12]. Its standard thickness ranges from 0.0127 cm to 0.1 cm, and also can be customized[12].

3.5 Limitations of model

This analysis considered only non-porous membranes. In addition, the pressure difference between the inside and outside of the membrane wall was not considered. If the hydrostatic pressure on the outside of the wall is great enough, it could influence oxygen transfer through the membrane.

A number of other assumptions were made when doing this analysis. Firstly, we assume that only oxygen will permeate through the membrane wall. But in reality, other gases, like nitrogen, carbon dioxide, etc., could also transfer, which would change oxygen partial pressure inside the tube, thus potentially affecting oxygen mass transfer rate. Also, we do not consider microbial activity. If microbial oxygen consumption at the membrane surface is rate-limiting, it will lead to an oxygen concentration at the outside of the membrane wall which is not zero. This would in turn influence oxygen mass transfer rate through the membrane wall. In addition, this model does not take into account the influence of temperature and wind into consideration. Parameters like dynamic viscosity, diffusion coefficient and pressure are all temperature related. And wind, air flow on the surface of lagoons, can have an influence on oxygen concentration in the atmosphere, gas velocity in the tube, and atmospheric pressure in the vicinity of the tube opening. When applying the technology to practice, it is important to consider these environmental factors, especially the temperature.

4.0 CASE STUDY – BUTLER FARM LAGOONS

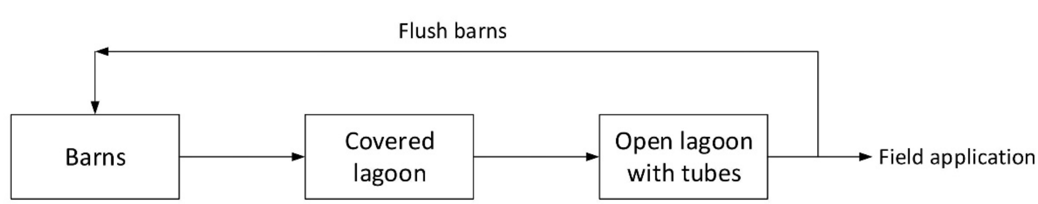
4.1 Butler Farm operation

The information in this section is from Bunk[13], Staunton et al[14], and Staunton and Aitken[15]. Butler Farm is an 8,000-head swine farm, located in the Cape Fear River Basin near Lillington in Harnett County, North Carolina. The farm uses lagoons and spray field system to manage its animal waste. There are two lagoons. Lagoon 1 has a maximum volume of 6.5 million gallons and a surface area of 96,100 ft^2. Lagoon 2 has a maximum volume of 4.5 million gallons and a surface area of 78,120 ft^2. Both lagoons are covered and a methane collection system has been installed. For this case study, it is envisioned that the smaller lagoon (Lagoon 2) could be converted to an open (uncovered) system, treating the anaerobically digested waste from Lagoon 1.

4.2 Application of dead-end membrane tubes

4.2.1 A proposed scheme for a full-scale system is illustrated in Figure 9.

Figure 9: A proposed scheme for a full-scale system



As a typical swine farm in North Carolina, waste entering the waste management system is a combination of urine, feces, waste drinking water and any additional fresh water used to wash barns. Waste first enters Lagoon 1, a covered anaerobic lagoon. In this lagoon, microorganisms will digest the organic matter in the swine excrement and convert it to methane, carbon dioxide, and other gases. Then, the anaerobically digested waste from Lagoon 1 will enter Lagoon 2. Note that for this project it is proposed to remove the cover from Lagoon 2 and employ the dead-end membrane tubes to further treat ammonium and residual biodegradable COD. Finally, effluent from Lagoon 2 will be used to flush the barns and sprayed onto on-site fields periodically in accordance with State regulations (Figure 9).

4.2.2 Oxygen demand

In order to know how many tubes are needed, we need to know the oxygen demand in the waste entering Lagoon 2. Ammonium and biodegradable COD are two main pollutants in digested waste that will consume oxygen in Lagoon 2.

When considering the oxygen demand from NH_4^+-N, the farm's annual liquid production and the mean lagoon NH_4^+-N concentration are combined to determine the farm's average daily nitrogen production. The annual liquid production is assumed to be equivalent to the volume of liquid sprayed annually, i.e., 5,818,060 L/year[13]. So daily liquid production is 15,940 L/d. The average NH_4^+-N concentration in the lagoons is 2,340 mg NH_4^+-N/L[13]. And the proportion of oxygen required for complete oxidation of ammonium to nitrate is 4.57 mg O^2/mg NH_4^+-N. Then the daily oxygen demand is calculated as follows:

$$15{,}940\ \frac{L}{d} \times 2{,}340\,\frac{mg\ NH_4{}^+ - N}{L} \times 4.57\,\frac{mg\ O_2}{mg\ NH_4{}^+ - N} = 170{,}459{,}172\ \frac{mg\ O_2}{d} \quad (21)$$

As for the oxygen demand from biodegradable COD, the average concentration of biodegradable COD in digested waste is 3,810 mg O_2/L[14]. So daily oxygen demand from COD is calculated as follows:

$$15{,}940\ \frac{L}{d} \times 3{,}810\,\frac{mg\ O_2}{L} = 60{,}731{,}400\,\frac{mg\ O_2}{d} \quad (22)$$

Thus, the total oxygen demand should be

$$170{,}459{,}172\ \frac{mg\ O_2}{d} + 60{,}731{,}400\frac{mg\ O_2}{d} = 231{,}190{,}572\frac{mg\ O_2}{d} \tag{23}$$

4.2.3 Tubes needed

If the PDMS tubes in the previous calculation (R=2 cm, thickness=0.015 cm, L=200cm) are used, it can provide a mass transfer rate of 19,151 mg O_2/d. Thus, the number of tubes needed is

$$231{,}190{,}572\ \frac{mg\ O_2}{d} \div 19{,}151\ \frac{mg\ O_2}{d} = 12{,}072\ tubes \tag{24}$$

And the surface area of the lagoon that each tube is responsible for is

$$\frac{78{,}120\ sqft}{12{,}072\ tubes} = 6.5\ \mathrm{sqft/tube} \tag{25}$$

The volume of waste that each tube can treat per day is

$$\frac{15{,}940\ \frac{L}{d}}{12{,}072\ tubes} = 1.32\ L/d/tube \tag{26}$$

There are several factors that can reduce the number of tubes required for this case. First, it is possible that under the low-oxygen conditions at the aeration tube/liquid interface, nitrite-oxidizing bacteria might not be competitive[14,15]. Therefore, less oxygen would be required than for complete nitrification to nitrate. In addition, whether nitrite or nitrate is the final product of nitrification, either of these electron acceptors could oxidize the biodegradable COD remaining in the Lagoon 1 effluent. Finally, if anaerobic ammonium oxidizing (anammox) bacteria were to grow in Lagoon 2, much of the ammonium in the waste could be removed anaerobically, thus reducing the overall oxygen demand even further[15].

5.0 GENERAL IMPLEMENTATION ISSUES

5.1 Membrane tube manufacture

From what we have discussed in the previous chapters, the tubes we want to use are desired to have a larger radius, smaller thickness and higher oxygen diffusion coefficient and partition coefficient. But they should also be in the acceptable radius and thickness ranges (R: 0.25 cm – 2.0 cm, δ: 0.015 cm – 0.1 cm). We might need more than ten thousand membrane tubes for one conventional swine lagoon, where tubes are inserted individually and each tube is responsible for about 7 ft^2 of lagoon surface. Then, in order to make tubes that could meet these requirements, the following issues should be considered.

5.1.1 Membrane material

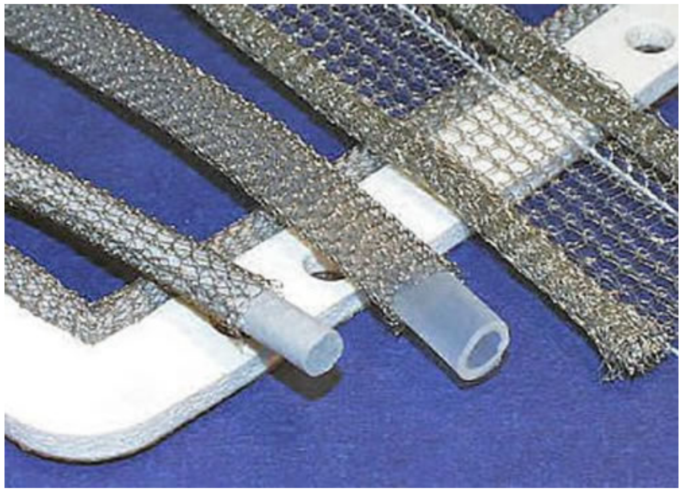
The membrane is the most important factor in this project. It is crucial to choose a kind of membrane material that provides a higher rate of oxygen mass transfer. We should also consider some practical issues such as whether the membrane is adequate for biofilm to grow on, whether there exists a commercial membrane with optimum thickness, or whether manufacturing of a new membrane would be required.

5.1.2 Membrane tubing

After choosing the membrane material, we should consider how to make tubes using the membrane sheets. The membrane sheets are very thin, so we consider to wrap the sheet around the outside of a tube model as structural support to keep the membrane from collapsing. The tube model must not prevent oxygen transfer or biofilm growth, or occupy too much surface area. For example, we can use stainless steel or nylon to make tube models like wire mesh. Or we can use stainless steel or plastic tubes with many small holes as the tube model. (Figure 10)

Figure 10: Tube model

Wire mesh[16]



Tube with holes[17]

5.2 Tube supporting system

After having the membrane tubes, we should consider how to put them in the lagoon. The membrane tube is very thin, the lagoon is very large, and thousands of tubes need to be put in the lagoon. A supporting system is needed to suspend the tubes in the lagoon liquid. And it is better if the system is easy to build and not too expensive.

Floating modules might be a good idea. We can make the membrane tubes in modules just like MBR membrane modules. In the module, there is a rectangular or hexagonal floating board with a certain numbers of holes in which membrane tubes can be put (see Figures 11, 12). The floating board can be made from stainless steel or plastic. The size and the number of tubes of each module can be decided considering the ease of manufacture and management.

For maintenance, if the membrane tubes need to be checked, washed or replaced, we just need to pull out the modules. This method then helps to manage a large quantity of thin membrane tubes more easily.

Figure 11: Sketch of floating modules

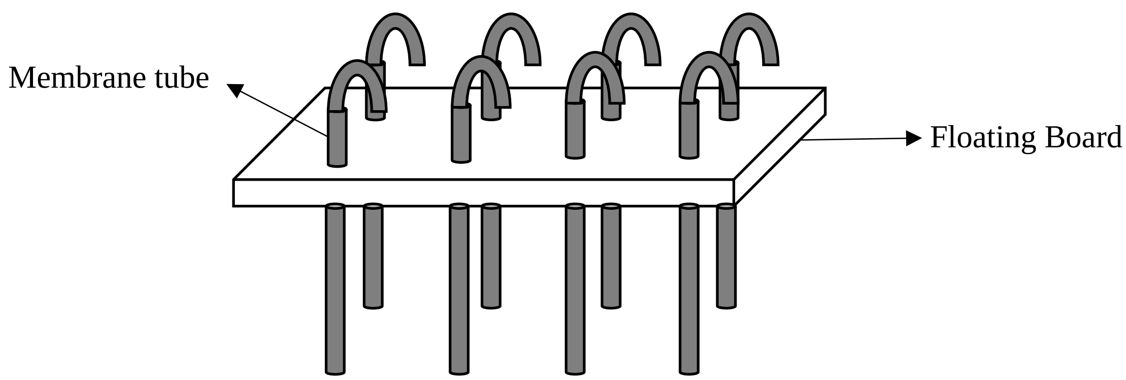
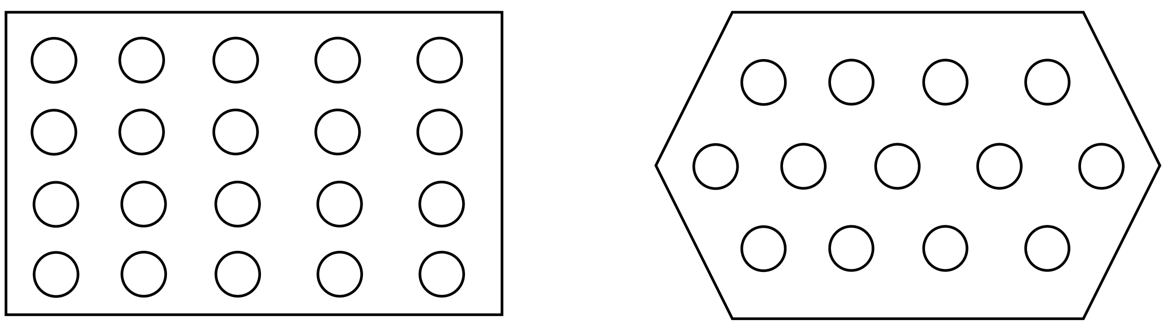


Figure 12: Rectangular or hexagonal floating board



5.3 Maintenance issues

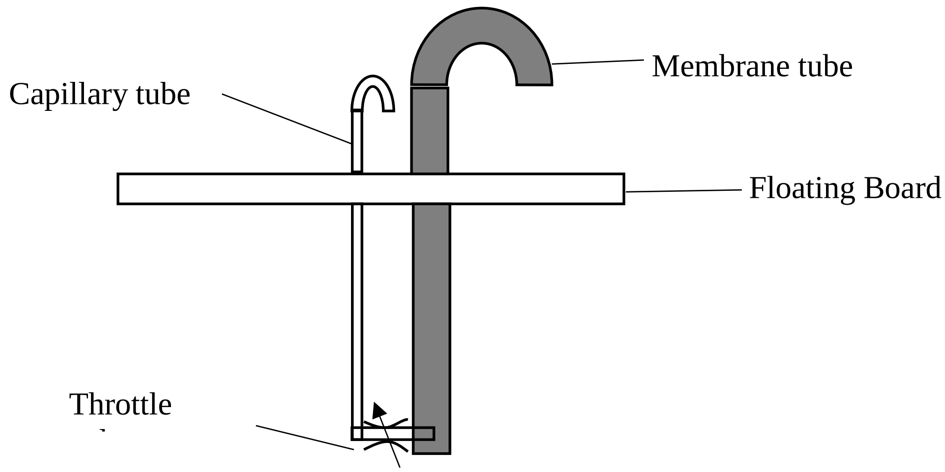
During operation, membrane tubes might be out of operation because of a leak or water accumulated inside from condensation. Then the tube needs to be repaired or changed. There are two ways to do maintenance. One is aiming at single tubes, the other is aiming at modules.

5.3.1 Single tube

If we want to know exactly which tube is out of work, we can use some technology in the tube which can inform us when the tube is damaged. For example, we can put a sensor inside the tube. If a tube leaks, water will enter the tube and accumulate inside. Once water touches the sensor, we will be informed in some way that there is water inside the tube. And then we can change that specific tube.

Besides sensors, we can also use capillarity (see Figure 13). A capillary tube is used to show whether there is water inside the membrane tube. The bottom of the capillary tube is inserted in the membrane tube with a throttle valve. The top of the capillary tube is above the floating board. When water accumulates inside the tube, the water will enter the capillary tube. As the valve is a throttle valve, once the water enters capillary tube, it will never go back. So if water continues entering capillary tube, at some point the water will reach the top of tube and drip down. In this way, if we see a membrane tube whose capillary tube aside has water dripping down, this membrane tube must have water inside.

Figure 13: Water detector



5.3.2 Modules

Because there would be thousands of membrane tubes in the lagoon, it can be very difficult to find a single tube that is out of work. Instead, we can check modules regularly. An important issue regarding checking modules is how to get to the modules and pull them out as the lagoon is so large. There are many different ways. We can use a boat to get to the modules, or build walkways on the lagoon. If the walkway is a solid material, it can also reduce ammonia volatilization from the lagoon liquid, and keep liquid at a stable temperature. Gantry or cable retrieval systems can also be used, but can be more expensive.

6.0 CONCLUSION

After calculations based on the model I built, I found that there is nearly no oxygen concentration gradient inside the tube. Thus, the model can be simplified in a way that the tube is treated as a homogeneous unit. The rate of oxygen diffusing out through the membrane can be calculated using the following equation.

$$M = \frac{2\pi R D_m k_g}{\delta}\int_0^L C\,dx \approx \frac{2\pi R D_m k_g}{\delta} C_0 L$$

From the equation above, it is not hard to find that a larger tube radius, smaller thickness, longer tube length, and a higher oxygen diffusivity of membrane material could provide a higher mass transfer rate. And if cost is related to the amount of membrane material required, a smaller thickness will be the key point. After comparing oxygen diffusion rates in different polymers, I found that silicone membranes are more than 30 times more permeable than non-silicone stable polymers, which could be an ideal material for membrane tubing in this project.

At Butler Farm, the daily oxygen demand for oxidizing ammonium to nitrate and fully oxidizing biodegradable COD in the open lagoon is about 2.3 x 10^8 mg O_2 per day. Slightly more than 12,000 tubes would be needed to meet such oxygen demand. And each tube is responsible for 6.5 ft^2 of lagoon liquid. This does not seem unreasonable for a passive aeration system.

In order to implement this dead-end membrane tube concept in reality, we are considering wrapping the membrane sheet around the outside or inside of a tube model that would serve as a structural support, and then inserting the tubes into floating boards to form floating modules, which helps to manage a large quantity of thin membrane tubes more easily.

7.0 FUTURE WORK

In model formulation, a lot of assumptions were made. For example, I assumed that there is only oxygen transferring through the membrane wall, and that oxygen concentration at the outside of membrane wall is zero. In the future, it is possible to build a model with fewer assumptions, which will better model real-world passive aeration.

This project only studied the technology in theory. We could further do laboratory studies to see whether the membrane tube can provide such oxygen mass transfer rate as calculated in the model. Additionally, before applying the technology to real conventional swine lagoons, the organisms grown on membrane tubes should be studied. As in the proposed passive aeration system, the microbial activity could be more complicated.

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